Opportunities for Higgs Physics at Future Lepton-Nucleon Colliders

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Nov. 16, 2016

Outline

1. Future projects of ep colliders: LHeC & FCC-he
2. Higgs boson production in ep collision
   - Single production
   - Pair production
3. Collider type consideration for Higgs physics
4. Higgs physics opportunities at the LHeC:
   - Bottom and charm Yukawa
   - Anomalous hVV and htt couplings
   - Invisible Higgs decay
   - Exotic Higgs decay $h \rightarrow \phi\phi \rightarrow 4b$
5. Conclusion and Discussion

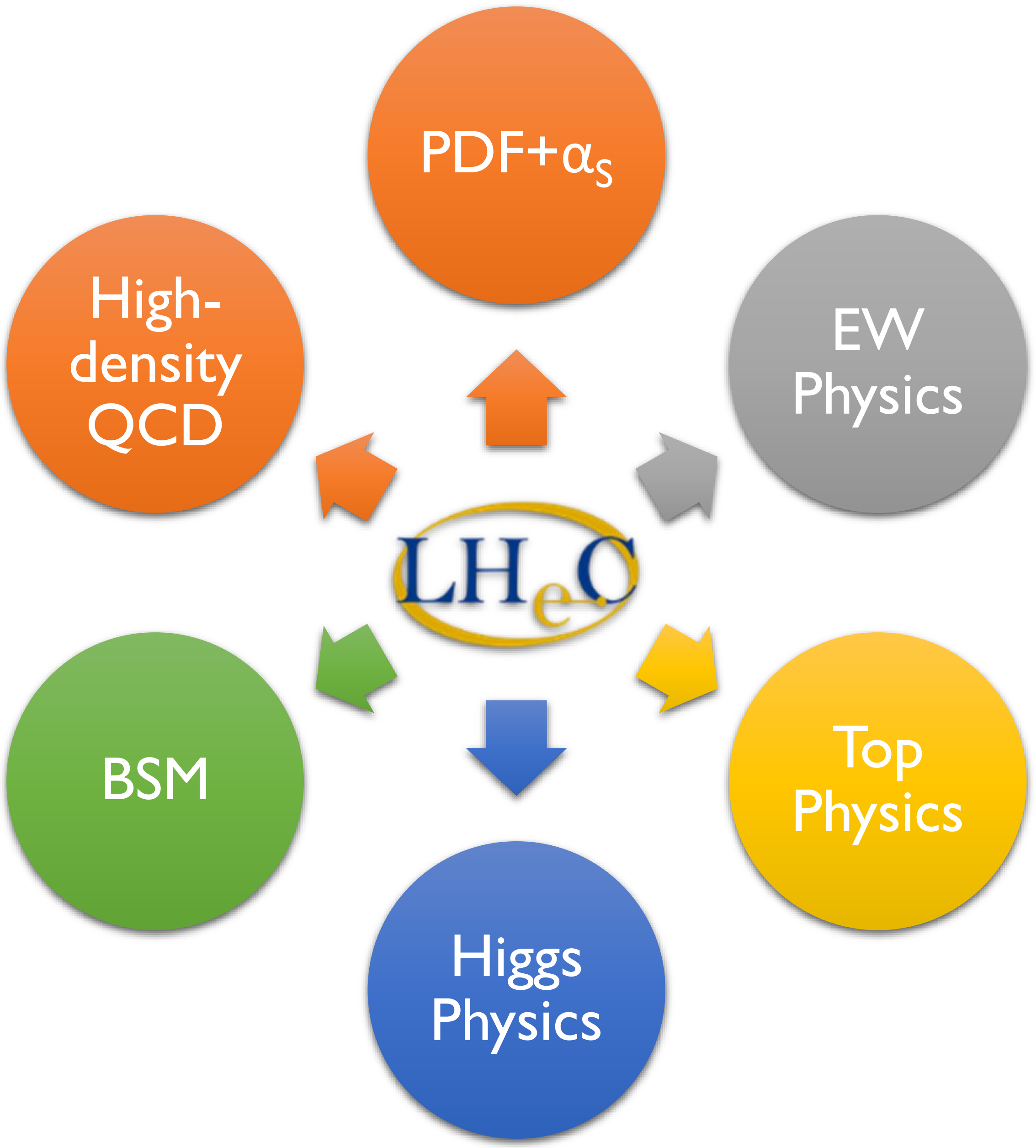
Future Projects of ep Colliders

See talk by M. Klein on Nov. 15

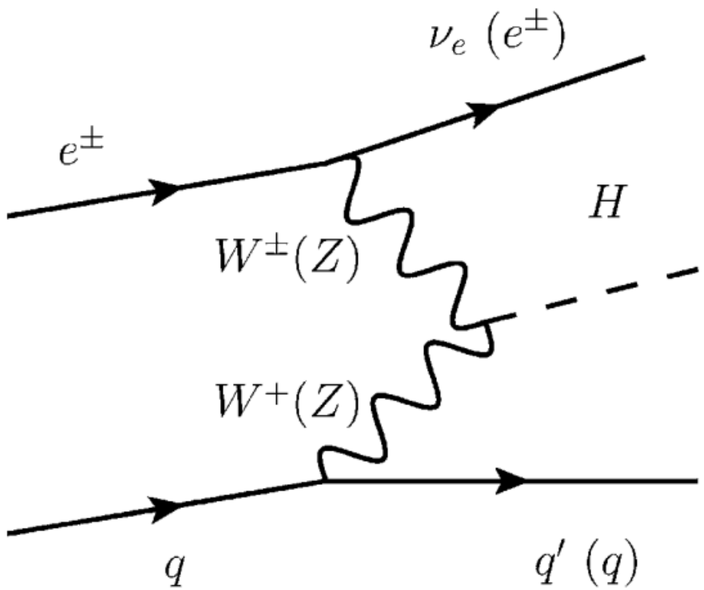
- LHeC
  - Using 7 TeV HL-LHC proton beam
  - 60 GeV electron (possibly with -80% polarization)
  - Luminosity as high as 1 ab^{-1}
  - Very large detector acceptance
  - Nearly free of pile-up
  - Expected to run synchronously with HL-LHC

- FCC-he
  - Using 50 TeV FCC-hh proton beam
  - 60 GeV electron (possibly with -80% polarization)
  - Luminosity as high as O(1 ab^{-1})
  - Very large detector acceptance
  - Nearly free of pile-up
  - Expected to run synchronously with FCC-hh

$\times 2$


PDF+α_s
EW Physics
Top Physics
Higgs Physics
BSM
High-density QCD
LHeC

Higgs Boson Production in ep Collision: Single Production



$$P^T_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{8\pi^2}\,\frac{1+(1-x)^2}{x}\,\frac{p_T^2}{(p_T^2+(1-x)M_V^2)^2},$$

$$P^L_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{4\pi^2}\,\frac{1-x}{x}\,\frac{(1-x)M_V^2}{(p_T^2+(1-x)M_V^2)^2},$$

$$\sigma(fa\to f'X) \approx \int dx\, dp_T^2\, P_{V/f}(x,p_T^2)\, \sigma(Va\to X).$$

- VBF-like topology for CC and NC production
- Understanding using effective W approximation:
  - No divergence when the pT of final state quark tends to zero, in contrast to QCD parton.
  - Because of the 1/x behavior for the gauge boson distribution, the outgoing parton energy (1-x)E tends to be high.
  - At high pT, the contribution from the longitudinally polarized gauge bosons is relatively suppressed

Higgs Boson Production in ep Collision:

Single Production

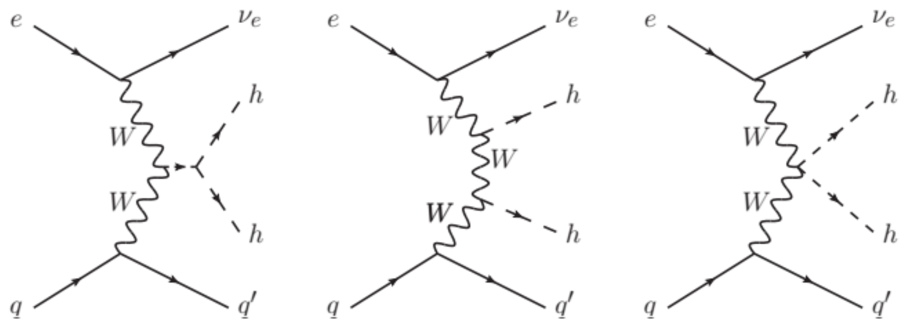
Uta Klein, DIS2015

Total event rates for 1ab^{-1}.

√s= **1.3 TeV** (CC - LHeC, NC - LHeC) √s= **3.5 TeV** (CC - FHeC)

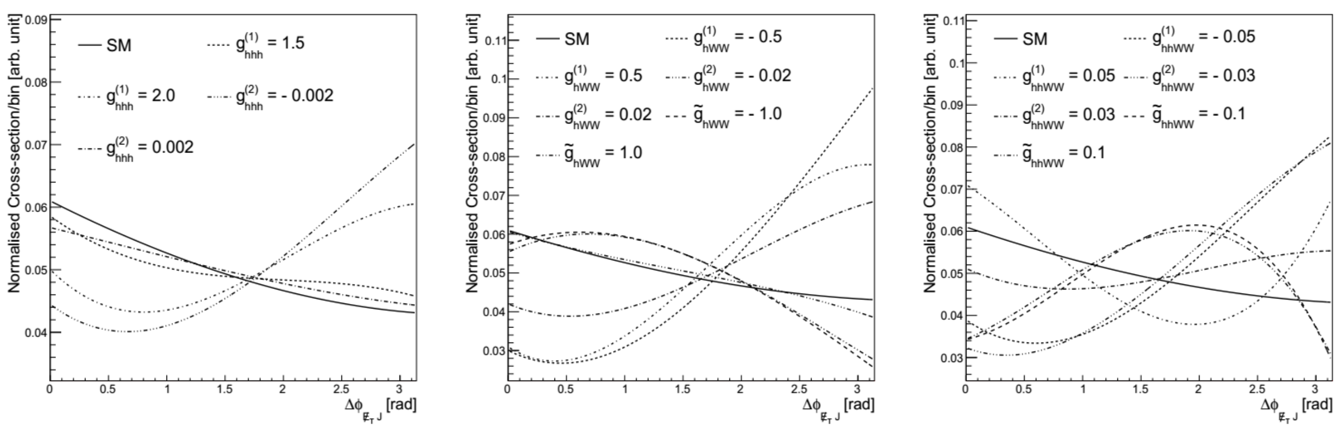
Higgs in $e^- p$		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

Higgs Boson Production in ep Collision: Pair Production



- **LHeC cross section (0.02fb) is too small=>FCC-he is needed (0.43fb).**
- Azimuthal angle between MET and the forward jet is sensitive to new physics.

M. Kumar, et al., 1509.04016 (Submitted to PLB)



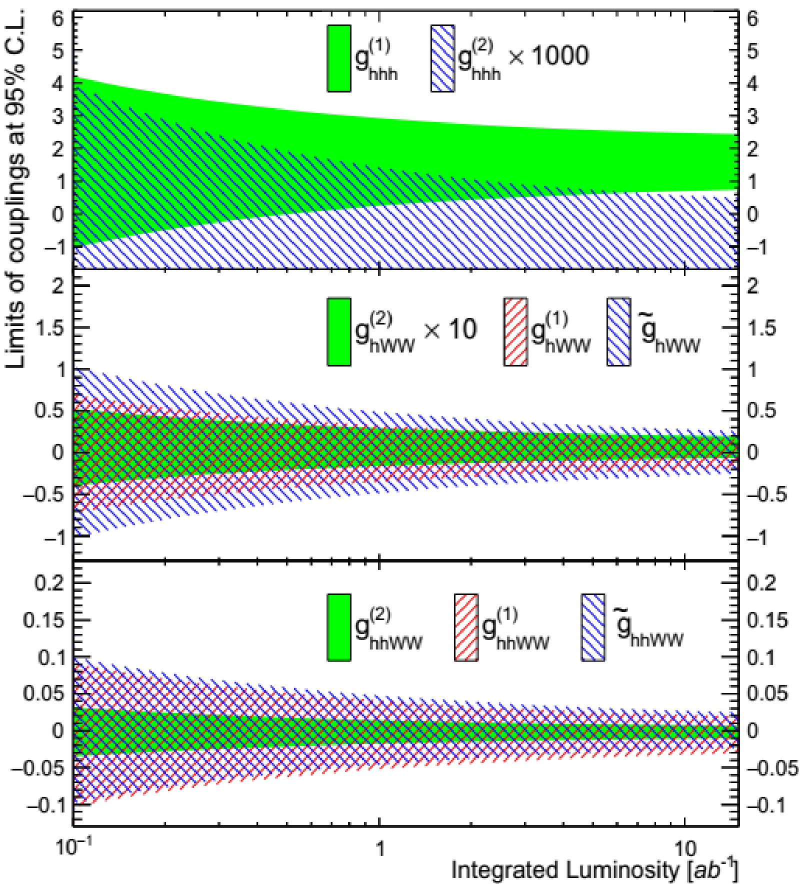
$$\mathcal{L}^{(3)}_{hhh} = \frac{m_h^2}{2v}(1 - g^{(1)}_{hhh})h^3 + \frac{1}{2}g^{(2)}_{hhh}h\partial_\mu h\partial^\mu h,$$

$$\begin{aligned}\mathcal{L}^{(3)}_{hWW} =& -\frac{g}{2m_W}g^{(1)}_{hWW}W^{\mu\nu}W^\dagger_{\mu\nu}h \\ & -\frac{g}{m_W}\left[g^{(2)}_{hWW}W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \text{h.c.}\right] \\ & -\frac{g}{2m_W}\tilde{g}_{hWW}W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu}h,\end{aligned}$$

$$\begin{aligned}\mathcal{L}^{(4)}_{hhWW} =& -\frac{g^2}{4m_W^2}g^{(1)}_{hhWW}W^{\mu\nu}W^\dagger_{\mu\nu}h^2 \\ & -\frac{g^2}{2m_W^2}\left[g^{(2)}_{hhWW}W^\nu\partial^\mu W^\dagger_{\mu\nu}h^2 + \text{h.c.}\right] \\ & -\frac{g^2}{4m_W^2}\tilde{g}_{hhWW}W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu}h^2.\end{aligned}$$

Higgs Boson Production in ep Collision:

Pair Production



$$
\begin{aligned}
\mathcal{L}^{(3)}_{hhh} &= \frac{m_h^2}{2v}(1 - g^{(1)}_{hhh})h^3 + \frac{1}{2} g^{(2)}_{hhh}\, h\partial_\mu h \partial^\mu h, \\
\mathcal{L}^{(3)}_{hWW} &= -\frac{g}{2m_W} g^{(1)}_{hWW} W^{\mu\nu} W^\dagger_{\mu\nu} h \\
&\quad - \frac{g}{m_W}\left[g^{(2)}_{hWW} W^{\nu} \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.} \right] \\
&\quad - \frac{g}{2m_W} \tilde{g}_{hWW} W^{\mu\nu} \tilde{W}^\dagger_{\mu\nu} h, \\
\mathcal{L}^{(4)}_{hhWW} &= -\frac{g^2}{4m_W^2} g^{(1)}_{hhWW} W^{\mu\nu} W^\dagger_{\mu\nu} h^2 \\
&\quad - \frac{g^2}{2m_W^2}\left[g^{(2)}_{hhWW} W^{\nu} \partial^\mu W^\dagger_{\mu\nu} h^2 + \text{h.c.} \right] \\
&\quad - \frac{g^2}{4m_W^2} \tilde{g}_{hhWW} W^{\mu\nu} \tilde{W}^\dagger_{\mu\nu} h^2.
\end{aligned}
$$

At the FCC-he the di-Higgs production is significant and through this channel one can probe accurately the Higgs boson self-coupling along with anomalous hhWW contributions, provided that integrated luminosities of more than 1 ab^{-1} may be achieved.

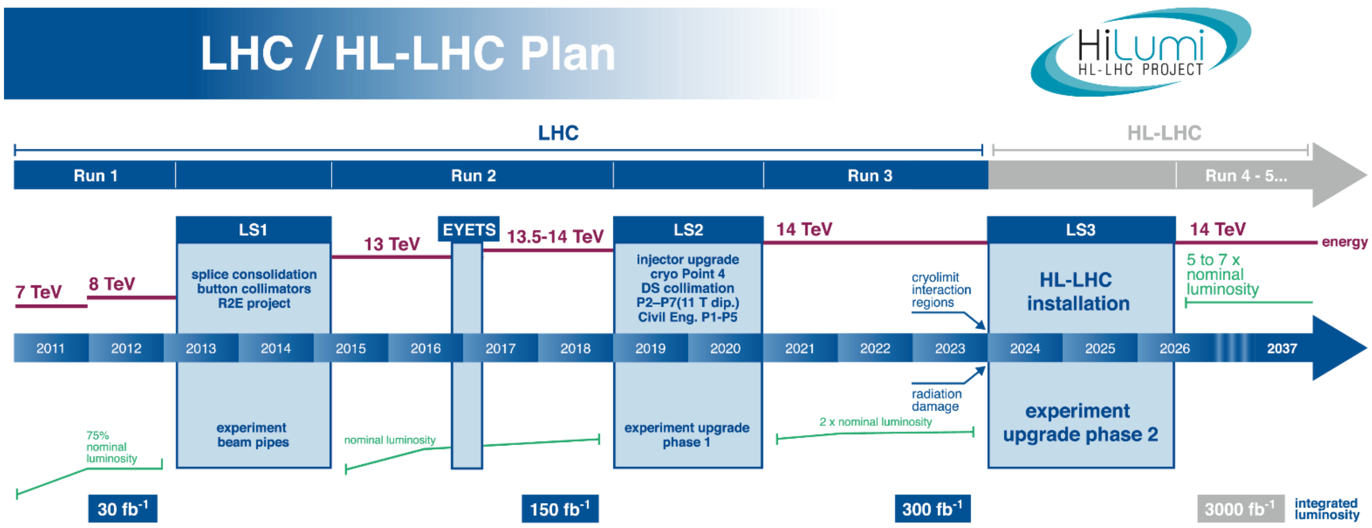
M. Kumar, et al., 1509.04016 (Submitted to PLB)

Collider Type Consideration for Higgs Physics: Usual Options

- (HL-)LHC
  - Large signal cross sections
  - Large backgrounds
  - Large pile-up
    - Higher thresholds needed to control systematics
    - Significant impact on the performance of objects like jet and MET

- Electron-positron collider
  - Small backgrounds
  - Pile-up negligible
  - Small signal cross sections
  - As long as the Br is not too small, e+e- machine will provide an ideal environment for precision Higgs studies.

Collider Type Consideration for Higgs Physics: The Role of the LHeC



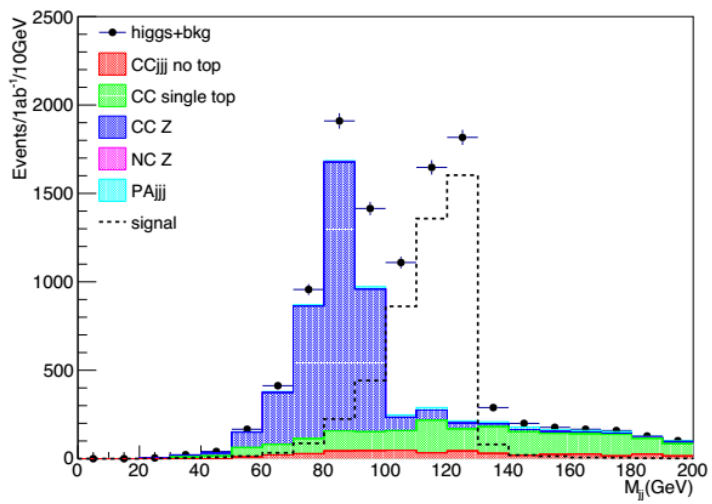
- A high luminosity electron-positron collider with sufficient center-of-mass energy will be ideal for Higgs measurements. However, there is a non-negligible probability that such facilities won't be available before the end of HL-LHC.
- Therefore, it is worthwhile to consider the option of adding an electron beam to HL-LHC which may maximize its physics potential. (High luminosity for ep is also important.)

Higgs Physics Opportunities at the LHeC: Bottom and Charm Yukawa

- Classical channel h→bb at LHeC.
- CDR and updated cut-based studies done by Tokyo Institute of Technology Group (Masahiro Kuze et al.)

Updated by Masahiro Tanaka, May 2016

- $1ab^{-1}$ is assumed
- Photo production events can be reduced to 10% if forward electron tagging is applied
- Mass of 1st and 2nd minimum η b-jets



Number of events in signal region
100 < M_{bb} < 130 GeV

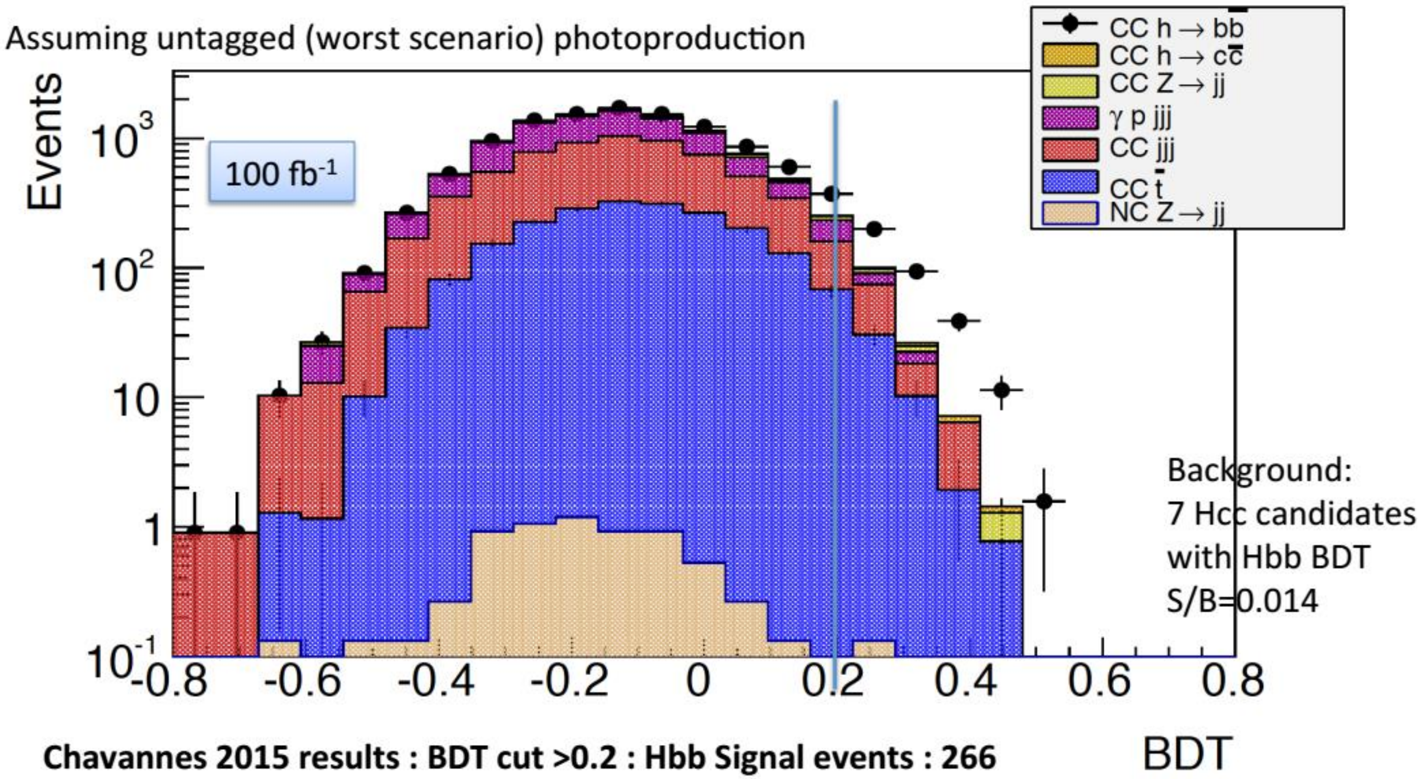
signal: 3822 +- 47
CCjjj no top: 125 +- 15
CC single top: 421 +- 19
CC Z: 164 +- 12
NC Z: 0
PAjjj: 40 +- 11
$S/\sqrt{B}$: 139.6 +- 3.2
σ_g/g : 0.0095

- Photo production events is now almost negligible
- Error of coupling constant is ~1% considering statistical error only

7

Higgs Physics Opportunities at the LHeC: Bottom and Charm Yukawa

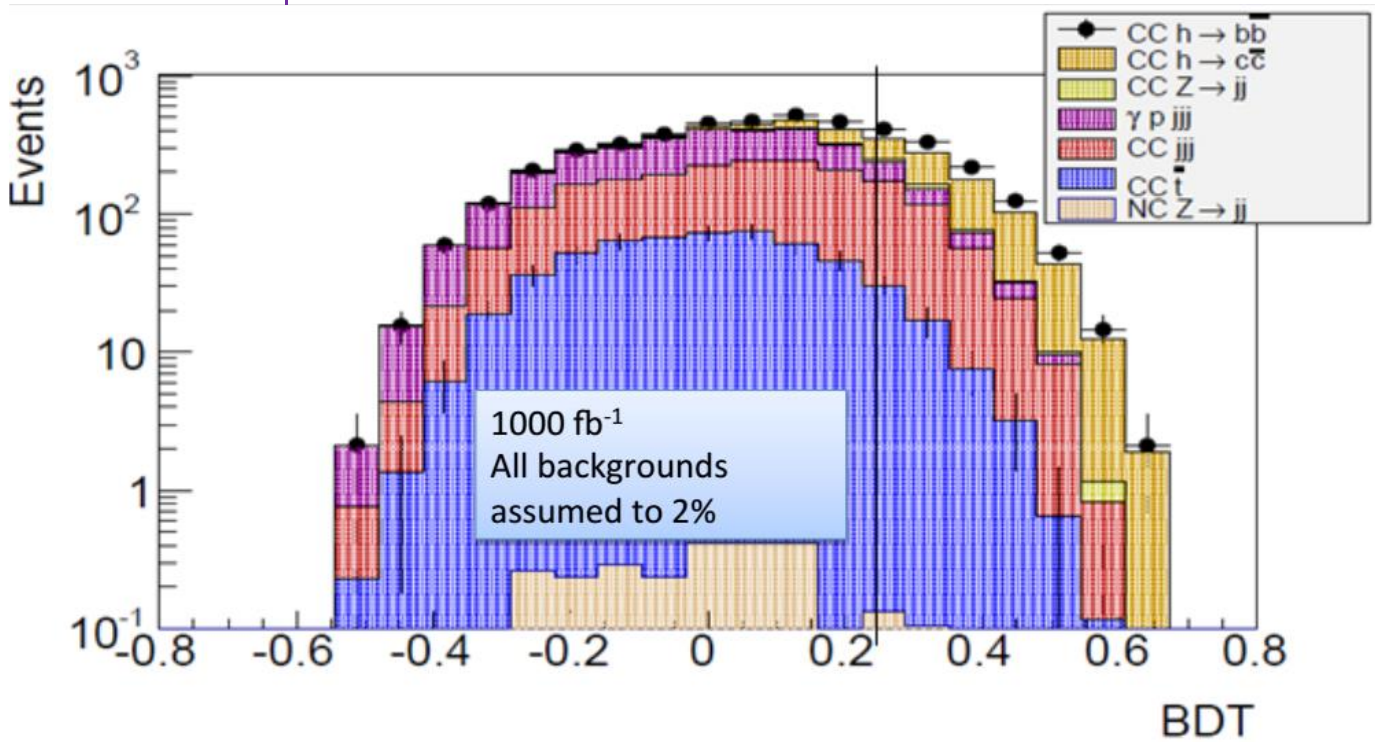
Uta Klein, LHeC workshop 2015.



- Using jet lifetime tags and BDT.
- Bottom Yukawa measured to 1.5% precision with LHeC 1 ab^{-1}.

Higgs Physics Opportunities at the LHeC: Bottom and Charm Yukawa

Uta Klein & Daniel Hampson



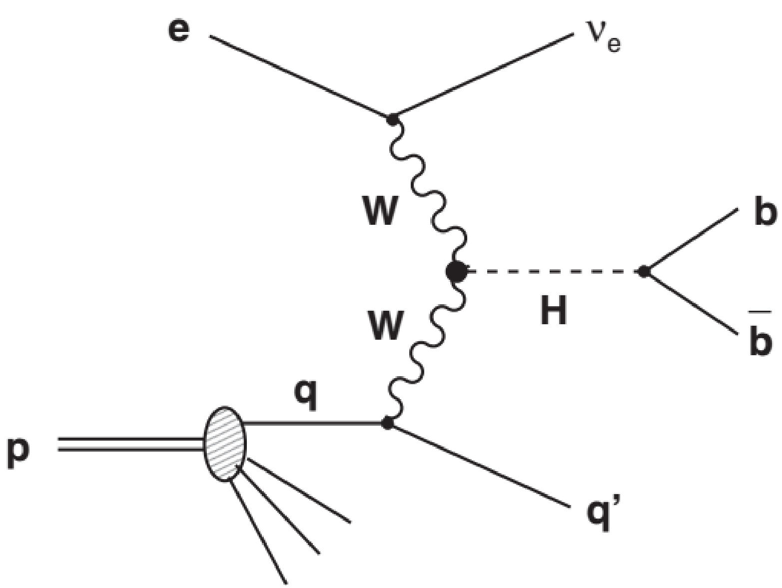
- Using jet lifetime tags and BDT. R=0.5 anti-kt jets and half nominal vertex resolution.
- Charm Yukawa measured to 5% precision with LHeC 1 ab^{-1}.

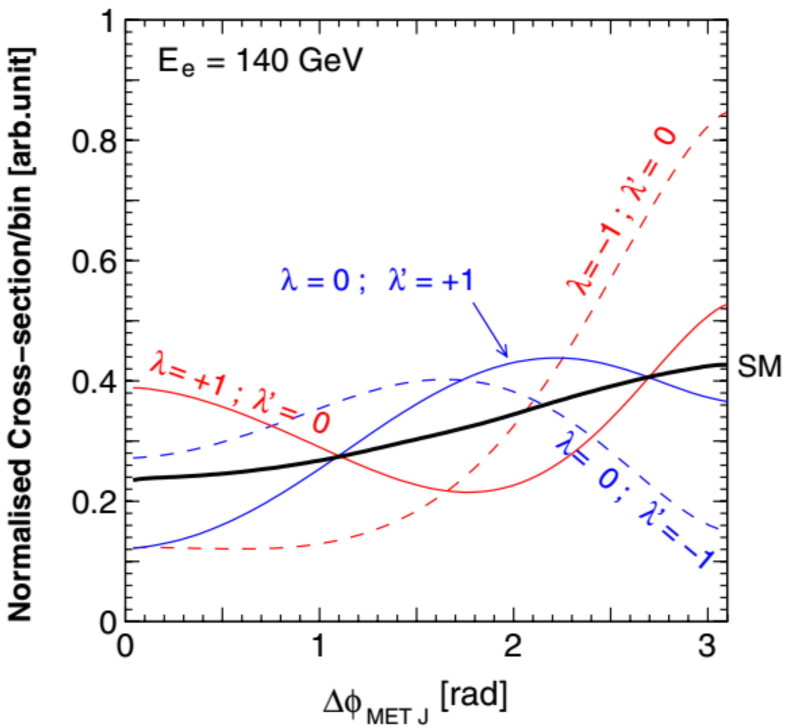
Higgs Physics Opportunities at the LHeC: Anomalous hVV Couplings

S. Biswal, R. Godbole, B. Mellado, S. Raychaudhuri

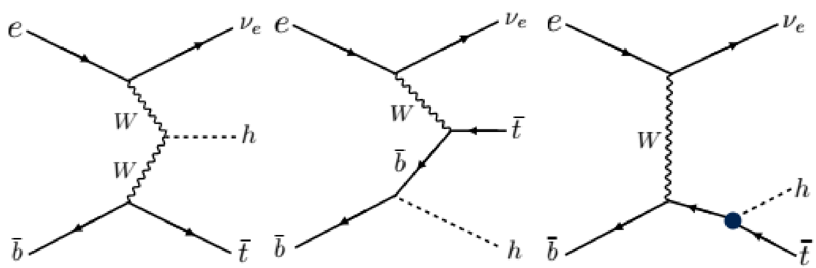
PRL 109, 261801 (2012)

$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_W}[\lambda(p\cdot q g_{\mu\nu} - p_\nu q_\mu) + i\lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma],$$



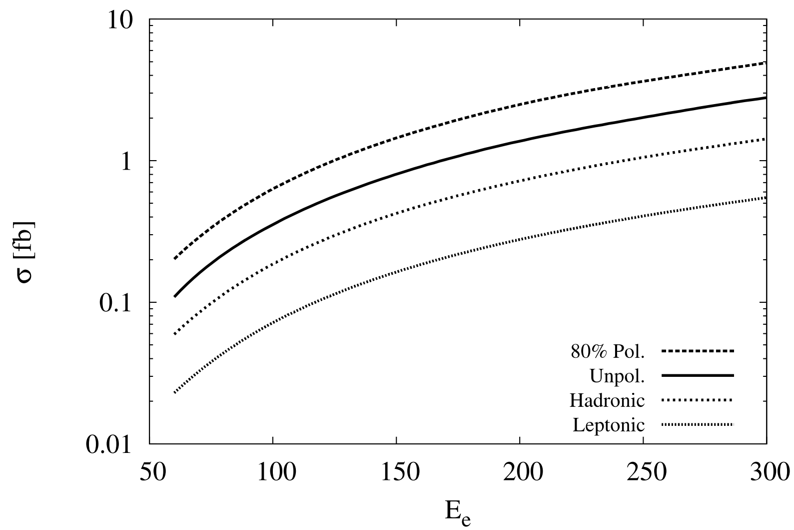


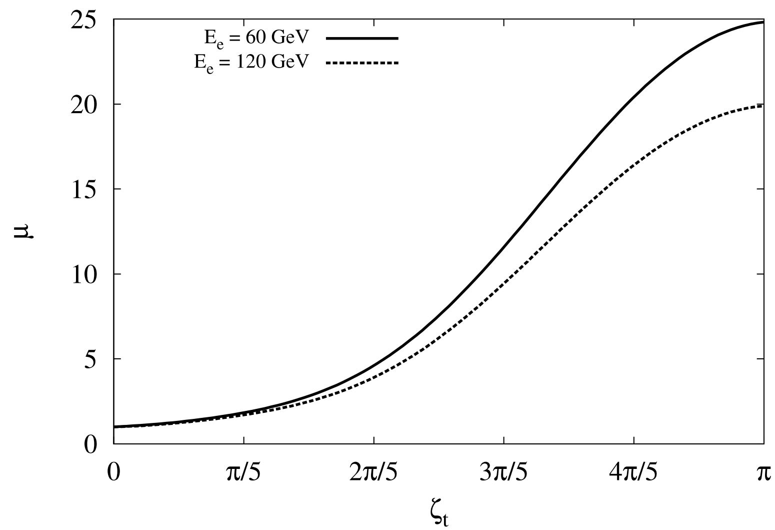
Higgs Physics Opportunities at the LHeC: Anomalous htt Couplings



B. Coleppa, S. Kumar, M. Kumar, B. Mellado, in progress.

$$\mathcal{L} = -i\frac{m_t}{v}\bar{t}\,[\cos\zeta_t + i\gamma_5 \sin\zeta_t]\; t\; h$$

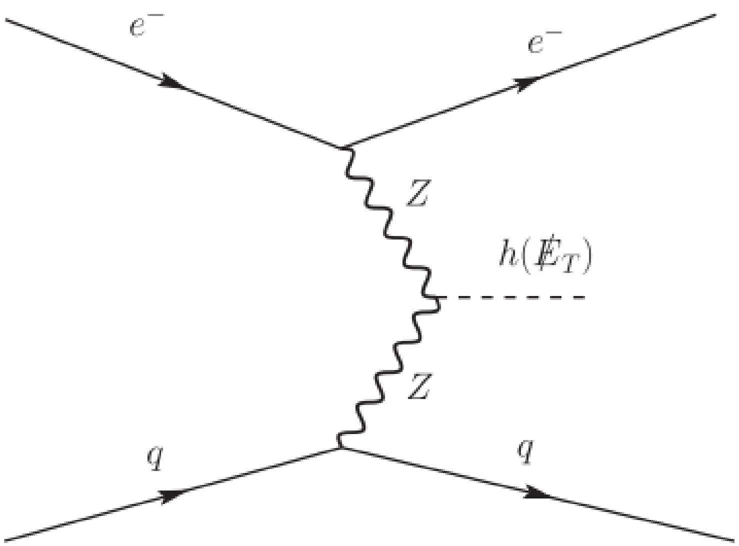




Strong increase of cross section for larger phase.

Higgs Physics Opportunities at the LHeC: Invisible Higgs Decay

Y. L. Tang, C. Zhang, S. Zhu, PRD 94 (2016) no.1, 011702



- Motivation: Important and well-motivated signature in many types of BSM & regular constraint on DM models, complementary to DM direct detection.
- Search channel at (HL-)LHC: VBF & ZH
- Signal at LHeC: NC Higgs. (~20 fb before Higgs decay and cuts, assuming -90% electron polarization)
- Major background: Wje, Wjv, Zje
- Event selection: basic cuts, MET cuts, VBF-like cuts, cuts on electron eta and inelasticity, lepton veto.

Higgs Physics Opportunities at the LHeC: Invisible Higgs Decay

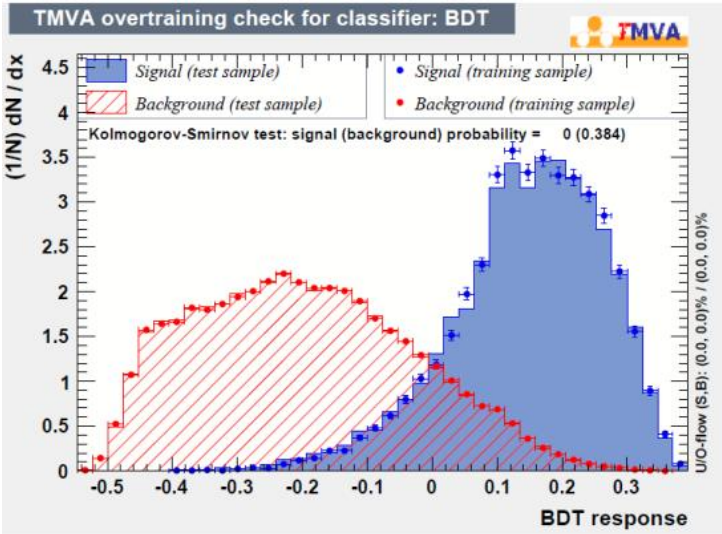
Parton level cut-based study

- Basic cuts & high MET threshold
- VBF-like cuts & cuts on electron pseudorapidity and inelasticity
- Lepton veto
- About 1.8fb signal (100% Br) and 3fb background after all cuts, probing 6% Br @ 2σ with 1 ab^{-1}.

Detector level study with MVA

- Probing 4.6% Br @ 2σ with 1 ab^{-1}.

  (Preliminary results by S. Kawaguchi and M. Kuze, Tokyo Institute of Technology)



Sensitivity comparison with HL-LHC: better than the traditional ZH channel.

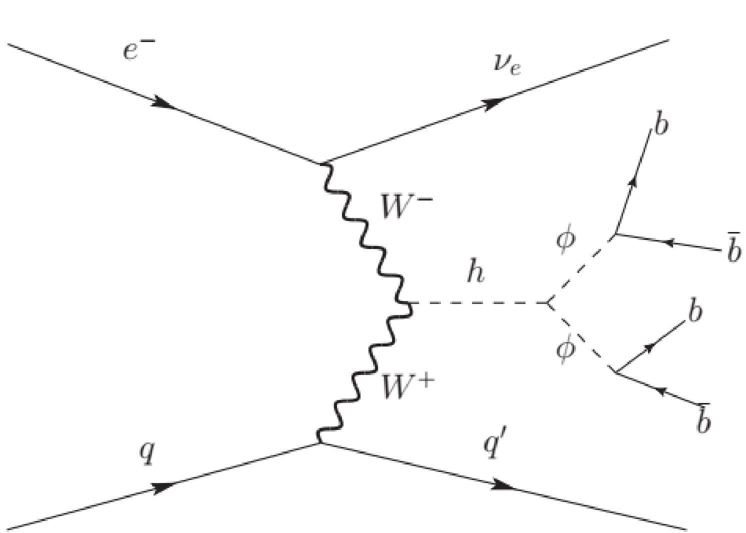
Comparison to VBF channel not applicable yet. (But should at least be comparable.)

Higgs Physics Opportunities at the LHeC:

Higgs to 4b

ϕ: a spin-0 particle from new physics.

$$eq \to \nu_e h q' \to \nu_e \phi\phi q' \to \nu_e b\bar{b}b\bar{b}q'$$



$$C_{4b}^2 = \kappa_V^2 \times \mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}^2(\phi \to b\bar{b})$$

S. Liu, Y. L. Tang, C. Zhang, S. Zhu, 1608.08458

- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC t/h/W/Z+jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is done at parton level.

ϕ mass range targeted in this study: [20,60]GeV, scanned in 1 GeV step.

Higgs Physics Opportunities at the LHeC: Higgs to 4b

- Jet energy smearing $\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \quad \alpha = 0.45 \text{ GeV}^{1/2}, \beta = 0.03$
- Basic cuts: requiring at least 5 jets satisfying $p_{Tj} > 20 \text{ GeV}, |\eta_j| < 5.0, \Delta R_{jj} > 0.4$

(Electron tagged events are excluded. Charged leptons are vetoed.)

- MET: (E_0=40GeV as default) $\not{E}_T > E_0$
- 4b-tagging At least 4 b-tagged jets in $|\eta| < 5.0$

$$\text{(A)}\ \epsilon_b = 70\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$$

$$\text{(B)}\ \epsilon_b = 70\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$$

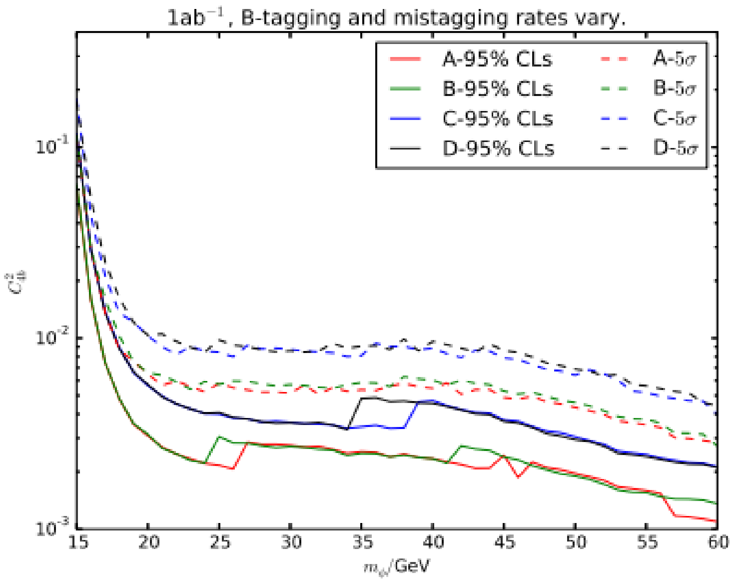
$$\text{(C)}\ \epsilon_b = 60\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$$

$$\text{(D)}\ \epsilon_b = 60\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$$

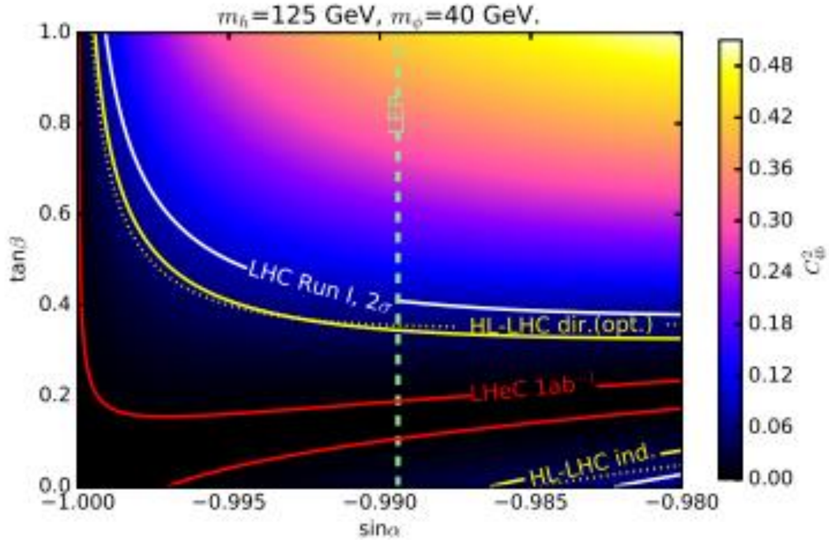
- 4b invariant mass window: $|m_{4b} - m_h| < 20 \text{ GeV}$
- 2b invariant mass window: for the "correct" grouping $|m_{2b,i} - m_\phi| < 10 \text{ GeV},\ i = 1, 2$

Higgs Physics Opportunities at the LHeC: Higgs to 4b

LHeC 1 ab^{-1} sensitivity



Sensitivity comparison in Higgs Singlet Model



- 95% CLs upper limit of C_{4b}^2 for 20, 40, 60 GeV phi mass with 1 ab^{-1}: 0.3%, 0.2%, 0.1% (E_0=40GeV)
- For E_0=60GeV, corresponding limits change to: 0.5%, 0.4%, 0.2%
- Better sensitivity than HL-LHC is guaranteed.

Contents

Well-Motivated & Extremely Rich Signatures!

D. Curtin et al., Phys.Rev. D90 (2014) no.7, 075004

Conclusion and Discussion

- Future ep colliders LHeC and FCC-he have an extremely rich physics program in which Higgs-related measurements play an important role, due to cleaner environment compared to concurrent hadron colliders.
- Higgs pair production can be studied at FCC-he.
- Single Higgs production can be studied at the LHeC to measure bottom and charm Yukawa, anomalous hVV couplings, invisible Higgs decay, $h \rightarrow \phi\phi \rightarrow 4b$ and other exotic decays, with better or comparable sensitivities compared to HL-LHC, making LHeC a very interesting and important candidate for precision Higgs studies in the HL-LHC era.

Backup

LHeC Detector Setup for Bottom Yukawa Study (Tokyo Group)

Setup of LHeC detector

- Coverage:
  - Calorimeter: $|\eta|<5$ Tracking: $|\eta|<4.7$
- Jet reconstruction:
  - Anti k_T algorithm with ΔR =0.7
- HCal resolution

$$\frac{\sigma}{E} = \frac{35\%}{\sqrt{E}} + 3\% (|\eta| < 2) \qquad \frac{\sigma}{E} = \frac{45\%}{\sqrt{E}} + 5\% (2 < |\eta| < 5)$$

- ECal resolution

$$\frac{\sigma}{E} = \frac{35\%}{E} \oplus \frac{7\%}{\sqrt{E}} \oplus 0.7\% \ (|\eta| < 3)$$

$$\frac{\sigma}{E} = \frac{20\%}{\sqrt{E}} \oplus 2\% \ (3 < |\eta| < 4)$$

$$\frac{\sigma}{E} = \frac{40\%}{\sqrt{E}} \oplus 10\% \ (4 < |\eta| < 5)$$

- B-tag
  - $|\eta| < 3.0$
  - B-jet ID: 60%
  - C-jet mis-ID: 10%
  - Light jet mis-ID: 1%